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EVIDENCE FOR GRAVITY SCALING AND IMPLICATIONS FOR EXPLOSION CRATERS

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ABSTRACT

Crater data have been examined from recent hypervelocity impact and chemical explosion experiments conducted in accelerating frames. Data have been identified from experiments for which the conditions of similitude have been very nearly achieved. Examination of these data from similar experiments indicates that fourth-root or gravity scaling is the rule which best relates crater dimensions to the energy release of impacting projectiles or explosives. Implications for chemical and nuclear explosion cratering are that in model experiments where the gravitational field is constant the specific energy and dimensions of the explosive must be scaled as the fourth-root of explosion energy release. Additionally, medium properties must be appropriately scaled in similar experiments. Because of the impracticability of realizing the constraints imposed on model experiments by similitude requirements attention in future experiments should be focused on the sources of similarity violation and their influence on empirical relationships derived from experiments. Experiments in accelerating frames with both explosive sources and hypervelocity impact projectiles offer one means for investigating effects of similitude violation. To further elucidate the question of crater scaling, experiments in accelerating frames may be conducted which most nearly achieve the conditions of similitude required.

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INTRODUCTION

The phenomena relating to craters produced by explosives or by impacting bodies are not well understood. In attempts to better understand the mechanisms and effects associated with the cratering process small scale experiments are conducted. From small scale or model experiments information is obtained which in principle can be related to large-scale events or prototype experiments such as the impact of meteor bodies on planetary surfaces or the energy release of nuclear explosions. Since the magnitude of energy release associated with nuclear explosions and meteors is often so large, modeling represents the only experimental method available for study of full scale cratering events. In practice, however, implementation of the modeling technique is difficult and in many cases impossible.

The means for performing model experiments are indicated in scaling rules derived from dimensional analysis (Chabai, 1977) or similarity analysis (Schmidt and Holsapple, 1978). One result of these analyses is that crater dimensions should scale as the cube-root or the fourth-root of the explosion or impact energy depending on whether or not gravity is considered important to the cratering process.

The history of scale model experiments presents a confusing picture. Early explosive cratering experiments (Lampson, 1946; COE, 1960) with small chemical explosives (less than 50 kg TNT) revealed that cube-root scaling described the crater data, i.e., crater dimensions were proportional to the cube-root of the explosive energy release. Experiments in Nevada alluvium with buried TNT charges of mass 50 to 10^6 kg demonstrate unambiguously that neither cube-root nor fourth-root scaling prevails. Rather, the empirical observation from these experiments is that crater dimensions are proportional to, or scale as, the 1/3.4 power of TNT energy release (Nordyke, 1962; Chabai, 1965). A host of data from surface burst explosions in various soil and rock media (Vortman, 1968, 1977) provide the result that crater radius and crater depth each scale differently with explosive energy. Furthermore, the crater radius and depth are found to be proportional to powers of energy release which, in general, differ significantly from 1/3 or 1/4.

Experiments with chemical explosives in accelerating frames (Viktorov and Stepanov, 1960; Johnson et al., 1969; Rodionov, 1970) and in centrifuges (Schmidt, 1977) have clearly established the influence of gravitational fields on the size of craters produced. Hypervelocity impact experiments (Gault and Wedekind, 1977) in accelerating frames have also shown that crater size is affected by the magnitude of the gravity field. The effect of atmospheric pressure on explosive crater size has been dramatically demonstrated in experiments by Herr (1971) and by Johnson et al. (1969). All of these small scale experiments clearly indicate that the gravity field is significant in the cratering process.

The superabundance of crater data collected to date from large scale field explosives has not, in fact, resulted in reliable scaling rules. Instead, empirical relationships among dimensionless variables have been established which are largely limited to particular explosives and to specific media (Vortman, 1968; Nordyke, 1977). These relationships may be used with confidence primarily as an interpolative tool in the same medium and with the same explosive. They cannot be considered reliable for application to different media, to different explosives or in extrapolation to the much larger energy releases from nuclear explosives or meteoritic impacts.

That reliable scaling rules have not been obtained from attempted model experiments may be a consequence of not realizing similitude in the model experiments. Inherent in the empirical relationships obtained is a reflection of those violations of the similitude requirement. The degree of violation may vary with the cratered medium, with the type of explosive, with explosive size, and with conditions of the model experiment. The source and degree of violation of similitude is not readily identifiable. Inability to scale medium properties such as density, strength, modulus, layering or explosive properties such as specific energy and Chapman-Jouguet pressure lead to absence of similitude in model experiments and, hence, to empirical relationships rather than scaling rules. Rarely in actual experiments have the conditions imposed by the demands of similitude been met. In view of this, we should attempt to better understand the deviations from expected scaling laws and to establish new experimental environments where the constraints of similitude may more easily be met.

SCALING RULES AND SIMILITUDE

Acknowledging the influence of gravity fields in crater formation, as established by small scale laboratory experiments, a dimensional analysis (Chabai, 1977; Gault and Wedekind, 1977) or similarity analysis (Schmidt and Holsapple, 1978) may be made on the variables deemed significant to crater formation by explosive charges or by impacting projectiles. Relationships among dimensionless variables or Π-terms are obtained. For scaled crater radius the result is

$$r\left(\frac{\rho g}{E}\right)^{1/4} = f_1\left\{d\left(\frac{\rho g}{E}\right)^{1/4}, \frac{p}{\left(\rho^3 g^3 E\right)^{1/4}}, C\left(\frac{\rho}{g^3 E}\right)^{1/8}, \frac{Y}{\left(\rho^3 g^3 E\right)^{1/4}}, a\left(\frac{\rho g}{E}\right)^{1/4}, q\left(\frac{\rho}{g^3 E}\right)^{1/4}\right\}. \quad (1)$$

Notation is illustrated in Figure 1. Analogous relationships are obtained for crater depth and volume. Target material properties, density, sound speed (compressibility) and strength are represented by ρ, C and Y, respectively. Explosive properties are indicated by E, the total energy release, q, the explosive specific energy and a, the charge radius. The explosive charge burial depth, d, is an independent variable. Hydrostatic pressure is represented by p and g is the acceleration due to gravity. For impacting spherical projectiles E is taken to be the kinetic energy, q the specific kinetic energy and a, the projectile radius. It should be noted that the explosive burial depth, d, is not relevant to the impact cratering case (Figure 1). Each of the terms of Equation (1) are dimensionless and are scaled variables; for example, the scaled radius is $\Pi_r^f = r(\rho g/E)^{1/4}$.

Equation (1) is equivalently written

$$\Pi_r^f = f_1\left(\Pi_d^f,\ \Pi_p^f,\ \Pi_C^f,\ \Pi_Y^f,\ \Pi_a^f,\ \Pi_q^f\right) \quad . \tag{2}$$

The scaling rules indicated by the Π^f-terms are referred to as gravity scaling or fourth-root scaling rules.

When gravity is considered to be unimportant to the cratering process, the familiar cube-root scaling rules are obtained:

$$r\left(\frac{\rho C^2}{E}\right)^{1/3} = f_2\left\{ d\left(\frac{\rho C^2}{E}\right)^{1/3},\ \frac{p}{\rho C^2},\ \frac{Y}{\rho C^2},\ a\left(\frac{\rho C^2}{E}\right)^{1/3},\ \frac{q}{C^2}\right\} \quad . \tag{3}$$

In Π-term notation Equation (3) is written

$$\Pi_r^c = f_2\left(\Pi_d^c,\ \Pi_p^c,\ \Pi_Y^c,\ \Pi_a^c,\ \Pi_q^c\right) \tag{4}$$

where superscript c denotes Π-terms for cube-root scaling.

The relative importance of the various Π-terms is not known a priori and the functions f_1 and f_2 are not given by dimensional analysis. This information must be obtained from experiments or theory. Determination of the importance of the various Π-terms in the cratering process represents a major challenge for future cratering experiments. Computer simulations of cratering (e.g., Bryan, et al., 1978) can also be expected to contribute to increased understanding in this area.

In a model experiment similitude is achieved if all the Π-arguments of the function, f, have values identical to those of the prototype experiment. When this is the case, Π_r will also have identical values for both model and prototype experiments. Only when similitude is realized in model experiments will the scaled quantities be representative of the prototype event.

When performing model explosive cratering experiments in a constant gravitational field and in a target medium of fixed density, Equation (1) requires that the target medium properties, C and Y, be changed such that the ratios $C/E^{1/8}$ and $Y/E^{1/4}$ remain constant so as to maintain the same Π_c^f and Π_Y^f values for both model and prototype experiments. The hydrostatic pressure, explosive charge radius and explosive specific energy must also be scaled as $E^{1/4}$ if similitude is to be realized. Since most of our experiments on explosive cratering are conducted in target media whose properties are generally unalterable, under fixed atmospheric pressure conditions and with explosives of a single type whose specific energy is constant, the conditions of similitude demanded by Equation (1) cannot be achieved. However, when performing model cratering experiments based on Equation (3), similitude is readily achieved by conducting experiments in the same medium with the same type of explosive.

Evidence from field experiments indicates that neither fourth-root nor cube-root scaling of crater dimensions is obtained. Laboratory experiments in accelerating frames have demonstrated the significance of gravitational acceleration on cratering. It seems reasonable to hypothesize that Equation (1) is the valid description for conducting model experiments and that field experiments to date conducted in a constant gravitational field are nonsimilar. Observations from these nonsimilar experiments provide empirical relationships among dimensionless quantities, e.g., the cratering, depth-of-burst curves $\Pi_r = f(\Pi_d)$ (Chabai, 1965; Nordyke, 1977). These relationships are not the scaling rules that would be obtained from experiments with similitude. While it is recognized that our usual experiments are not similar it is not known which of the variables, Π_p^f, Π_c^f, Π_Y^f, Π_a^f or Π_q^f, contribute most to violation of similitude and to what degree. Herr's (1971) experiments demonstrate that larger values of Π_r^f are produced by a decrease in Π_p^f. It seems reasonable to assume that an increase in target strength and in modulus (Π_Y^f and Π_c^f) would result in a smaller crater (decrease in Π_r^f). It might be expected then, that as experiments are conducted with larger explosions, in the same medium and in a constant gravitational field, the variables Π_p^f, Π_c^f and Π_Y^f take on a less significant role in violation of similitude. The same observation may be true for Π_a^f and Π_q^f; i.e., as the scale of the experiment is increased by employment of larger explosives, or projectiles with greater mass and velocity, the contribution to similarity violation from these sources diminishes and the experiments approach more nearly the conditions of similitude desired. Unfortunately, nature does not appear to be sufficiently accommodating to provide a target medium whose properties are uniform and constant. Consequently, the possibility of evaluating these speculations by field experiments seems remote indeed since field experiments in a constant gravitational field are nonsimilar and since target media occurring in nature are usually insufficiently homogeneous. For these reasons empirical relationships obtained in one medium cannot readily be applied to another target medium. Results for one explosive cannot be used with great confidence in cratering experiments with different explosives in the same medium. Also, extrapolation to larger explosive energies is uncertain.

Equation (1) indicates that to maintain similitude among cratering experiments in the same medium the product g^3E must be held constant among experiments. When the size of the explosive energy release is varied the value of g must be changed accordingly. The variable Π_q^f requires that q remain constant in experiments when g^3E is held fixed, so that the same explosive must be utilized for all experiments.

For hypervelocity impact experiments in the same target material the similitude requirement, g^3E = constant, demands that $q = (1/2)V^2$ or the impact velocity, V, remain fixed among experiments. It is seen from $\Pi_q^f/\Pi_a^f = q/ag$ that the product of projectile radius, a, and frame acceleration, g, must be invariant among impact experiments in the same medium.

The impracticality of varying target material properties prevents performance of cratering experiments with similitude when the gravitational field is constant. Explosive or impact cratering experiments in the same target medium must be conducted in accelerating frames if similitude is to be realized. For explosive cratering the same explosive must be used (Schmidt and Holsapple, 1978) and for impact cratering projectiles of varying radius must have the same velocity among experiments. The condition on frame acceleration, g, in these experiments is determined from ag = constant where a is charge radius or the radius of a spherically impacting projectile.

EXAMINATION OF DATA FROM CRATERING EXPERIMENTS CONDUCTED IN ACCELERATING FRAMES

Nearly 100 cratering experiments have been conducted by Gault and Wedekind (1977) in gravitational field environments ranging from 0.72 to 9.8 m/s^2. Aluminum spheres of radii 0.795, 1.590 and 3.175 mm impacted quartz sand targets at normal incidence with velocities ranging from 0.4 to 7 km/s. Crater diameters and crater formation times were measured. Results from one set of experiments by Gault and Wedekind are shown in Figure 2 for impacting spheres of the same size and kinetic energy. The dependence of crater radius on gravitational acceleration is shown ($g_E = 9.8\ m/s^2$). This dependence is $r \propto g^{-0.165 \pm 0.005}$* in opposition to the result provided by dimensional analysis, $r \propto g^{-0.250}$. Gault and Wedekind provide one plausible explanation for this deviation which is associated with the small, but nevertheless significant, shear strength effects exerted by the quartz sand medium during the cratering process. They also suggest the possibility of other unidentified factors, in addition to medium shear strength, which may be contributing to the discrepancy between measured and expected dependence of r on g.

An alternative explanation for the deviation between the experimental and dimensional analysis results may reside in lack of similitude among the experiments of the set illustrated in Figure 2. As discussed in the previous section, impact experiments in the same target medium require that among those experiments g^3E be constant for achievement of similitude. This condition forces the specific kinetic

* Uncertainty in value of scaling exponent is given at the 95% confidence level.

energy (or velocity) of impacting projectiles to be constant among all experiments and further, that the product of projectile diameter and gravitational acceleration, ag, be identical for all experiments. In the experiment set of Figure 2 only the condition for constant specific kinetic energy is met. In consequence, inability to conduct experiments with all similitude constraints satisfied may be the principal cause of the observed deviation.

Data from all sets of the Gault-Wedekind experiments have been examined in an effort to find multiple experiments for which the conditions of similitude are met. Only one pair of experiments was found that had the same scaled projectile radius, nearly the same value for g^3E and nearly the same value of the product ag. Information on, and data from, this pair of experiments (A and B) are listed in Table I.

The experiment pair, A and B, of Table I closely meets all the requirements of similitude. Velocities of the impacting projectiles are nearly identical. Values of g^3E and ag are nearly the same as necessary for similitude. Gravitational acceleration levels were significantly different and actual crater radii differed by more than a factor of 2. Each experiment represents considerably different conditions but maintains the constraints imposed by similitude. Values of the scaled crater radii for experiments A and B differ by less than 7%, which percentage is approximately the experimental uncertainty estimated for the actual crater radii. The agreement in values of the scaled radii is within limits of experimental error and could be interpreted as a verification of gravity scaling for projectiles impacting quartz sand. However, within the limits of experimental error, cube-root scaling is equally appropriate for these two experiments.

Also shown in Table I are data from explosion experiments conducted at different g-levels with a centrifuge (Schmidt and Holsapple, 1978). These experiments meet the similitude requirements of gravity scaling. As with the impact experiments values of π_r^f differ by less than 8% suggesting validity of gravity scaling.

Values of Π_r^c (or $r/E^{1/3}$) also differ by less than 8% suggesting that cube-root scaling is correct. The paucity of data strain such interpretations and do not permit firm conclusions. The need for additional gravity scaled experiments is evident.

To examine the competing hypothesis that the cube-root rule best describes results of model cratering experiments additional data from Gault and Wedekind and from Schmidt and Holsapple were examined. Three sets of data were isolated (Table II) which met the similitude conditions of cube-root scaling. Within each set of similar experiments, comparisons can be made of the values of $r/E^{1/3}$ (proportional to Π_r^c). For comparable changes in energy release, E, between model experiment pairs, the percentage differences in Π_r^c are comparable with those in Π_r^f. However, maximum percentage differences in Π_r^c within each set of similar impact experiments are seen to be considerably greater than the uncertainty error associated with experiments. Further, for each set of similar experiments one finds that as E increases, the cube-root scaled radius, Π_r^c, systematically decreases rather than remains constant. This observation is reminiscent of the cratering data from field experiments in alluvial soil of the Nevada Test Site (Chabai, 1965). There it was found that larger energy releases produced smaller cube-root scaled craters and that 1/3.4 scaling better described the data than did cube-root scaling. The limited amount of data from well-controlled laboratory model experiments in quartz sand with both hypervelocity projectiles and chemical explosives, appears to confirm the trend of results observed from large-scale chemical explosions in Nevada alluvium. These results demonstrate that cube-root scaling is inadequate for estimation of crater dimensions produced by prototype explosions using model experiment data.

From Equation (1) and Equation (3) it is seen that, among cratering experiments with similitude in a medium whose properties remain constant, crater radius is proportional to $(E/g)^{1/4}$ for gravity scaling and to $E^{1/3}$ for cube-root scaling. A plot of crater radius, r, versus effective energy release, $g_e E/g$, for each set of similar experiments provides information on the scaling exponent of E. Data from Tables I and II have been plotted in Figure 3. Least squares fits on the data sets determine the line slopes or scaling exponents of E and their corresponding standard deviations. Results of the least squares fits are summarized in Table III. From Figure 3 or Table II it is seen that neither a 1/4 value nor a 1/3 value for the exponent on effective energy release is demonstrated by the data. For the cube-root scaled experiments the exponent is less than 1/3 and for the gravity scaled experiments it is greater than 1/4. This result is similar to that obtained from field experiments in Nevada alluvium, even though in Nevada experiments conditions of similitude demanded by gravity scaling cannot be realized.

Laboratory experiments with similitude suggest that cube-root scaling is not valid. Data obtained to date from these laboratory experiments also fail to verify gravity scaling. However, in these experiments the influence of gravity on crater size is unambiguous. A reduction in crater radius by nearly a factor of 3 is observed in going from $g/g_e = 1$ to 451 (experiments 11-X and 644 of Tables I and II) and by more than a factor of 2 in going from $g/g_e = 1$ to 306 (experiments 13-O and 645). This result strongly supports gravity scaling as being more representative of the cratering process when similitude is achieved.

That the 1/4 exponent on energy for scaling crater radius has not been verified by the laboratory experiments may be a consequence of too few experiments or a consequence of some unidentified effect, such as strain rate, contributing to violation of similitude among experiments. Clearly more gravity scaled experiments are required to investigate the question further.

Conditions for one set of desirable experiments are shown in Figure 4. Illustrated in Figure 4 are those values of a and g necessary in experiments to obtain conditions of similitude with experiment A ($a = 1.59$ mm, $g = 5.02$ m/s^2) of Gault and Wedekind. Vertical grid lines in the figure indicate the frame acceleration levels available in the Gault-Wedekind experimental apparatus. Horizontal grid lines represent those pellet radii employed by Gault and Wedekind in their experiments. At 9.8 m/s the impacting pellet radius should be 0.814 mm, slightly greater than that (0.795 mm) used in experiment B. For the other acceleration levels, 7.91, 6.57, 2.65, 1.87, 1.18 and 0.72 m/s^2, accessible, the pellet radii should be 1.01, 1.22, 3.02, 4.27, 6.76 and 11.09 mm, respectively, in order to obtain similitude with experiment A. Among these experiments the velocity of impact must be constant and equal to that of experiment A (6.64 km/s). The energy range covered by such experiments would be more than 3 orders of magnitude.

Changing the velocity of impact for experiment A provides the ability to investigate another set of experiments having similitude and to examine more completely the validity of gravity scaling. Systematic investigation by experiments over a range of values of the similitude constraint parameters, g^3E and ag, would not only provide more extensive data for evaluation of scaling laws but would hopefully also identify those parameters which are most significant in realizing the conditions necessary for similitude.

CONCLUDING REMARKS

Recent laboratory experiments on impact and explosive cratering suggest that cube-root scaling is not valid, tending to confirm previous findings of large scale field experiments. These well-controlled laboratory experiments clearly establish the influence of the gravity field on crater size produced; however, the few experiments (5) performed with the similitude conditions required by gravity scaling have not verified quarter-root scaling. If gravity scaling is most appropriate for describing the cratering process then explosive cratering experiments conducted in the field are not similar since the gravitational field is constant and medium properties cannot be varied to achieve conditions of similitude. Data from field experiments provide empirical relationships among selected quantities such as dimensionless crater volume versus dimensionless depth of burial. Within these empirical relationships are embedded influences reflecting, in an unknown way, violation of similitude. An example of this is the 1/3.4 scaling rule derived from field experiments in Nevada alluvium. As a result, such empirically established cratering relationships cannot be employed with confidence in predicting crater dimensions produced in other media, in predicting crater dimensions produced by different explosives in the same medium and in predicting crater dimensions produced by much larger explosions whose energy release is considerably beyond the range of experimental experience.

During the past decade a multitude of field experiments in various media and with various explosives have produced still additional empirical relationships for relating crater size to explosive energy release. Unfortunately, these experiments have not furnished new insights into the basic questions of crater scaling. They have not identified the material properties most significant in the cratering process nor have they presented any information on conditions relating to violations of similitude. However, recent experiments in accelerating frames have offered the promise of gaining increased comprehension of the complex cratering process. A one gram explosive charge at an acceleration level of 500 times earth gravity can be used to simulate the cratering of a 125 ton charge in the earth's gravitational field. In accelerating frames cratering experiments may be performed under well-controlled conditions. Experiments may be conducted both with and without the similitude constraints of dimensional analyses satisfied. Systematic investigations may be made of the relative importance of medium properties in the cratering process, their contribution to violation of similitude constraints and their influence on cratering as a function of charge size.

Continued laboratory experimentation in impact and explosion cratering holds the potential, not available in field experiments, for supplying an increased understanding of the many empirical relationships derived from model field experiments. Computer calculations of explosion and impact cratering offer another promising avenue for investigation and additional comprehension. With this increased understanding we may expect to apply crater scaling rules with greater accuracy and confidence to the high energy regimes of interest which are beyond our ability to test.

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REFERENCES

Bryan, J. B., Burton, D. E., Cunningham, M. E. and Lettis, Jr., L. A.: 1978, A Two-Dimensional Computer Simulation of Hypervelocity Impact Cratering: Some Preliminary Results for Meteor Crater, Arizona, Proceedings of the Ninth Lunar and Planetary Science Conference (pp. 3931-3964), Pergamon Press, New York.

Chabai, A. J.: 1965, On Scaling Dimensions of Craters Produced by Buried Explosions, J. Geophys. Res., Vol. 70, No. 20.

Chabai, A. J.: 1977, Influence of Gravitational Fields and Atmospheric Pressures on Scaling of Explosion Craters, Impact and Explosion Cratering, Roddy, D. J., Pepin, R. O. and Merrill, R. B., editors, Pergamon Press, New York.

COE: 1960, Compendium of Crater Data, Tech. Rept. 2-541 Report 1, Corps. of Engineers, United States Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Gault, D. E. and Wedekind, J. A.: 1977, Experimental Hypervelocity Impact into Quartz Sand-II: Effects of Gravitational Acceleration, Impact and Explosion Cratering, Roddy, D. J., Pepin, R. O. and Merrill, R. B., editors, Pergamon Press, New York.

Herr, R. W.: 1971, Effects of Atmospheric-Lithostatic Pressure Ratio on Explosive Craters in Dry Soil, NASA-TRR-366, NASA Langley Research Center, Hampton, Virginia.

Johnson, S. W., Smith, J. A., Franklin, E. G., Moraski, L. K., and Teal, D. J.: 1969, Gravity and Atmospheric Pressure Effects on Crater Formation in Sand, J. Geophys. Res. Vol. 74.

Lampson, C. W.: 1946, Explosions in Earth, Effects of Impact and Explosions, Office of Scientific Research and Development, Washington, D.C., 1946.

Nordyke, M. D.: 1962, An Analysis of Cratering Data from Desert Alluvium, J. Geophys. Res., Vol. 67, No. 5.

Nordyke, M. D.: 1977, Nuclear Cratering Experiments: United States and Soviet Union, Impact and Explosion Cratering, Roddy, D. J., Pepin, R. O. and Merrill, R. B., editors, Pergamon Press, New York.

Rodionov, V. N.: 1970, Methods of Modeling Ejection with Consideration of the Force of Gravity, UCRL-Trans.-10476, Lawrence Livermore Laboratory, Livermore, California.

Schmidt, R. M.: 1977, A Centrifuge Cratering Experiment: Development of a Gravity-Scaled Yield Parameter, Impact and Explosion Cratering, Roddy, D. J., Pepin, R. O. and Merrill, R. B., editors, Pergamon Press, New York.

Schmidt, R. M. and Holsapple, K. A.: 1978, Centrifuge Crater Scaling Experiments I; Dry Granular Soils, DNA-4568F, Defense Nuclear Agency, Washington, D.C.

Viktorov, V. V. and Stepanov, R. D.: 1960, Modeling of the Action of an Explosive with Concentrated Charges in Homogeneous Ground, Translation SC-T-392, Sandia Laboratories, Albuquerque, New Mexico.

Vortman, L. J.: 1968, Craters from Surface Explosions and Scaling Laws, J. Geophys. Res., Vol. 73, No. 14.

Vortman, L. J.: 1977, Craters from Surface Explosions and Energy Dependence - A Retrospective View, Impact and Explosion Cratering, Roddy, D. J., Pepin, R. O. and Merrill, R. B., editors, Pergamon Press, New York.

TABLES

Table I. Impact and Explosion Experiments with Similitude Conditions Required by Gravity Scaling.

Table II. Impact and Explosion Experiments with Similitude Conditions Required by Cube-Root Scaling. $g = g_e = 9.8\ m/s^2$

Table III. Scaling Exponent on Effective Energy Release for Scaling Crater Radius from Impact and Explosion Experiments. Results of Least Squares Fits.

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Figure 3. Crater Radius in quartz sand as a function of effective energy release from gravity-scaled and cube-root scaled experiments.

Figure 4. The ag product constraint of similitude normalized to Experiment A of Table I. Horizontal grid lines represent radii of projectiles used by Gault and Wedekind. Vertical grid lines indicate g-levels accessible in Gault and Wedekind experiments.

TABLE I

IMPACT AND EXPLOSION EXPERIMENTS WITH SIMILITUDE CONDITIONS REQUIRED BY GRAVITY SCALING

EXP.	a (mm)	V (km/s)	g/g_e *	m (mg)	E (kJ)	q (kJ/g)	$(g/g_e)^3E$ (kJ)	ag/g_e	r (mm)	Π_a^f †	Π_r^f †
IMPACT EXPERIMENTS (1)											
A	1.590	6.64	0.51	47.1	1.038	22.0	0.138	0.811	90.5	3.05×10^{-3}	0.174
B	0.795	6.60	1.00	5.9	0.128	21.8	0.128	0.795	42.5	3.04×10^{-3}	0.163
EXPLOSION EXPERIMENTS (2)											
11-X	5.65	-	451	1340	7.18	5.34	6.59×10^8	2548	43.8	3.25×10^{-2}	0.252
11-0	5.65	-	451	1340	7.18	5.34	6.59×10^8	2548	43.1	3.25×10^{-2}	0.248
13-0	8.26	-	306	4080	22.7	5.56	6.50×10^8	2528	68.8	3.24×10^{-2}	0.269

(1) Data of Gault and Wedekind (1977)

(2) Data of Schmidt and Holsapple (1978)

* $g_e = 9.8$ m/s^2

† Quartz sand density = 1650 kg/m^3 for impact experiments and 1780 kg/m^3 for explosion experiments.

TABLE II

IMPACT AND EXPLOSION EXPERIMENTS WITH SIMILITUDE CONDITIONS REQUIRED BY CUBE-ROOT SCALING $g = g_e = 9.8$ m/s^2

EXP.	a (mm)	V (km/s)	m (mg)	E (kJ)	q (kJ/g)	r (mm)	$a/E^{1/3}$ (mm)/(kJ)$^{1/3}$*	$r/E^{1/3}$ (mm)/(kJ)$^{1/3}$*
IMPACT EXPERIMENTS (1)								
C	0.795	1.4	5.9	5.77×10^{-3}	0.980	30	4.43	167.26
D	0.795	1.4	5.9	5.77×10^{-3}	0.980	27.5	4.43	153.32
E	1.590	1.4	47.1	4.62×10^{-2}	0.980	48	4.43	133.81
F	3.175	1.4	375	3.68×10^{-1}	0.980	85	4.43	118.67
H	0.795	6.6	5.9	0.128	21.78	42.5	1.58	84.26
I	1.590	6.6	47.1	1.026	21.78	80	1.58	79.32
J	3.175	6.6	375	8.168	21.78	147.5	1.58	73.24
EXPLOSION EXPERIMENTS (2)								
642	5.65	-	1340	7.18	5.36	118	2.94	61.17
644	5.65	-	1340	7.18	5.36	120	2.94	62.20
643	8.26	-	4080	22.7	5.56	163	2.92	57.57
645	8.26	-	4080	22.7	5.56	164	2.92	57.92

(1) Data (Fig. 4) of Gault and Wedekind (1977).

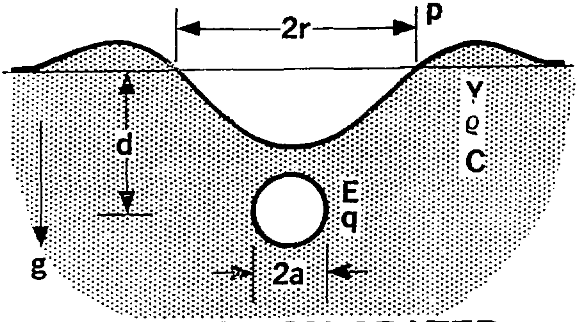
(2) Data of Schmidt and Holsapple (1978), d = o.

* Target sound speed, C, unknown; in a medium with constant properties $a/E^{1/3}$ and $r/E^{1/3}$ represent measures of the dimensionless Π^c-terms, $\Pi_a^c = a(\rho C^2/E)^{1/3}$ and $\Pi_r^c = r(\rho C^2/E)^{1/3}$.

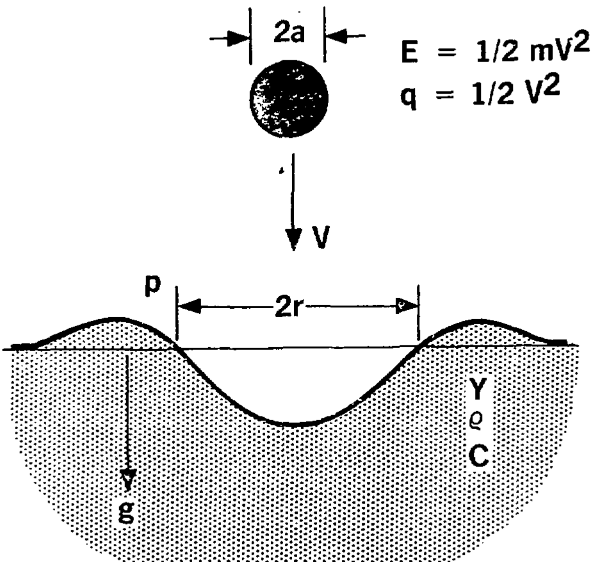
TABLE III

SCALING EXPONENT ON EFFECTIVE ENERGY RELEASE FOR SCALING CRATER RADIUS FROM IMPACT AND EXPLOSION EXPERIMENTS. RESULTS OF LEAST SQUARES FITS.

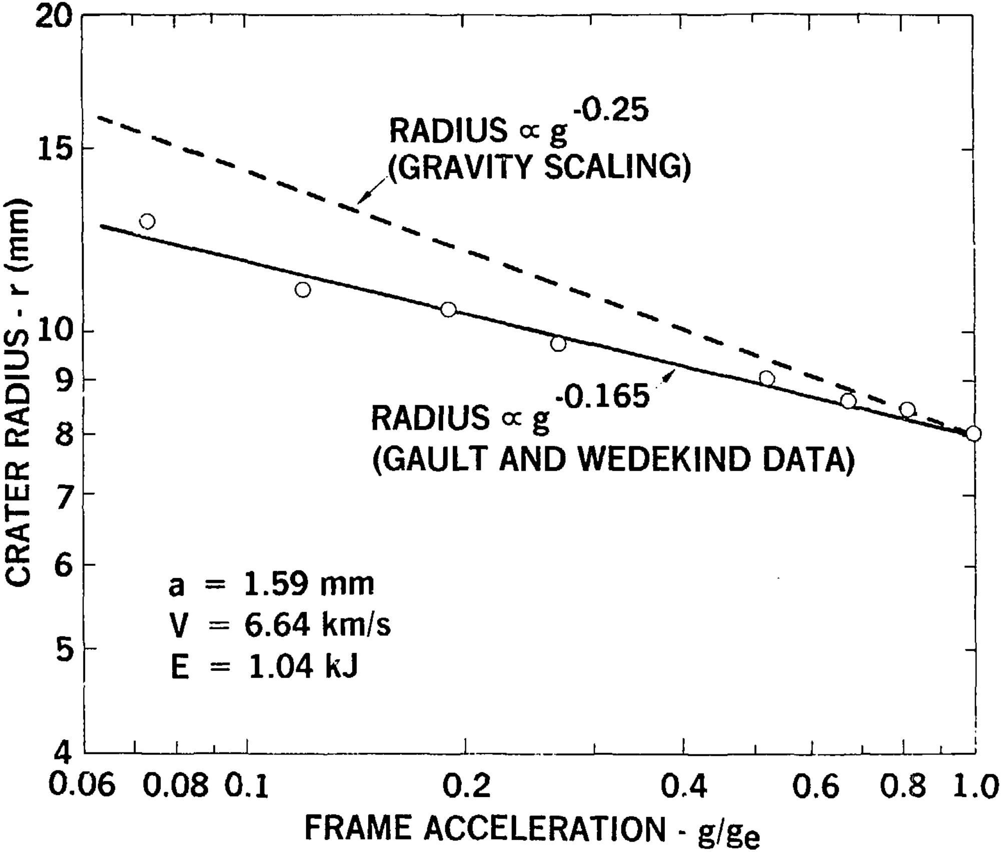
EXP. TYPE	SIMILITUDE CONDITIONS	NO. OF EXPERIMENTS	SCALING EXPONENT	STANDARD DEVIATION
Impact	Gravity	2	0.274	-
Explosion	Gravity	3	0.299	0.009
Impact	Cube-Root	4	0.260	0.014
Impact	Cube-Root	3	0.300	0.002
Explosion	Cube-Root	4	0.276	0.008



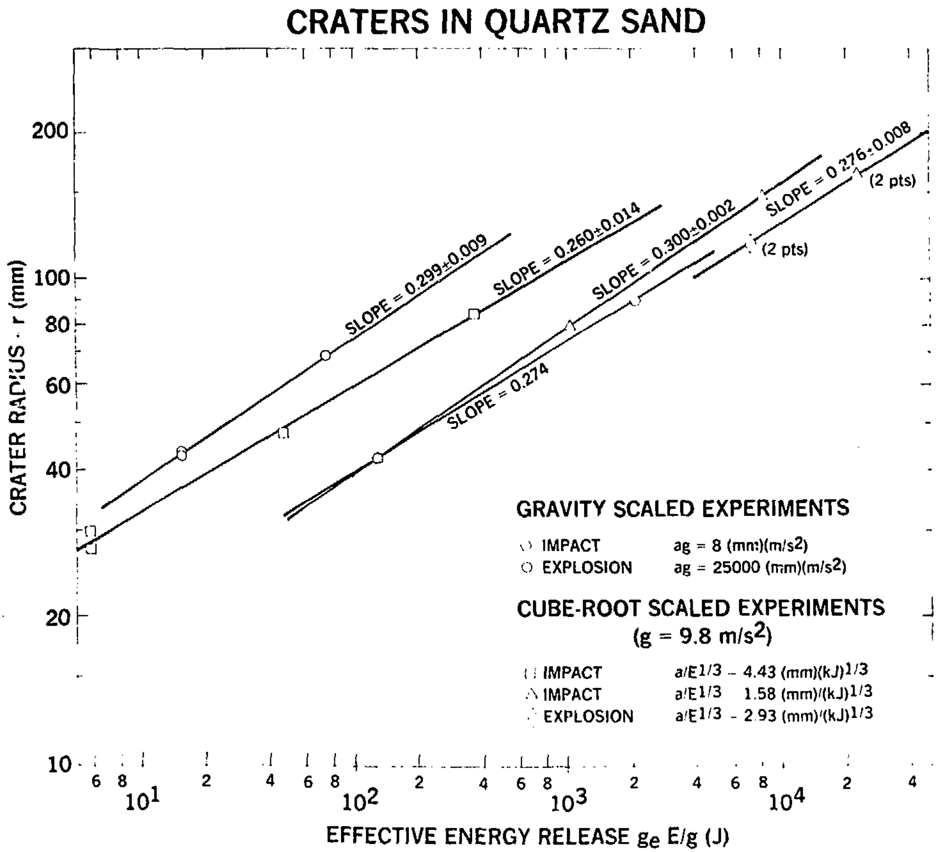
EXPLOSION CRATER



IMPACT CRATER



20
15
10
9
8
7
6
5
4
CRATER RADIUS - r (mm)
RADIUS ∝ g^-0.25
(GRAVITY SCALING)
RADIUS ∝ g^-0.165
(GAULT AND WEDEKIND DATA)
a = 1.59 mm
V = 6.64 km/s
E = 1.04 kJ
0.06
0.08
0.1
0.2
0.4
0.6
0.8
1.0
FRAME ACCELERATION - g/ge



CRATERS IN QUARTZ SAND
SLOPE = 0.299±0.009
SLOPE = 0.260±0.014
SLOPE = 0.300±0.002
SLOPE = 0.276±0.008
SLOPE = 0.274
(2 pts)
(2 pts)
CRATER RADIUS - r (mm)
200
100
80
60
40
20
10
EFFECTIVE ENERGY RELEASE g_e E/g (J)
10^1
10^2
10^3
10^4
GRAVITY SCALED EXPERIMENTS
IMPACT ag = 8 (mm)(m/s^2)
EXPLOSION ag = 25000 (mm)(m/s^2)
CUBE-ROOT SCALED EXPERIMENTS
(g = 9.8 m/s^2)
IMPACT a/E$^{1/3}$ - 4.43 (mm)(kJ)$^{1/3}$
IMPACT a/E$^{1/3}$ 1.58 (mm)/(kJ)$^{1/3}$
EXPLOSION a/E$^{1/3}$ - 2.93 (mm)/(kJ)$^{1/3}$

SIMILITUDE CONSTRAINT
$ag = 8$ (mm) (m/s^2)